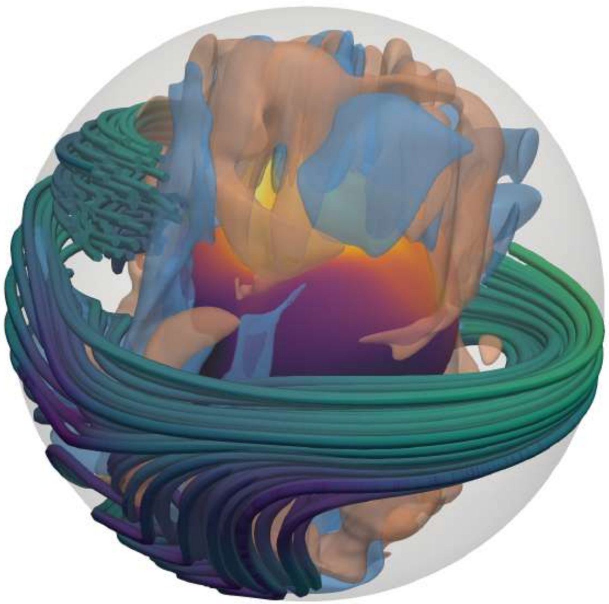
Gravitational waves from protoneutron star convection:

A probe into PNS dynamo and magnetar formation



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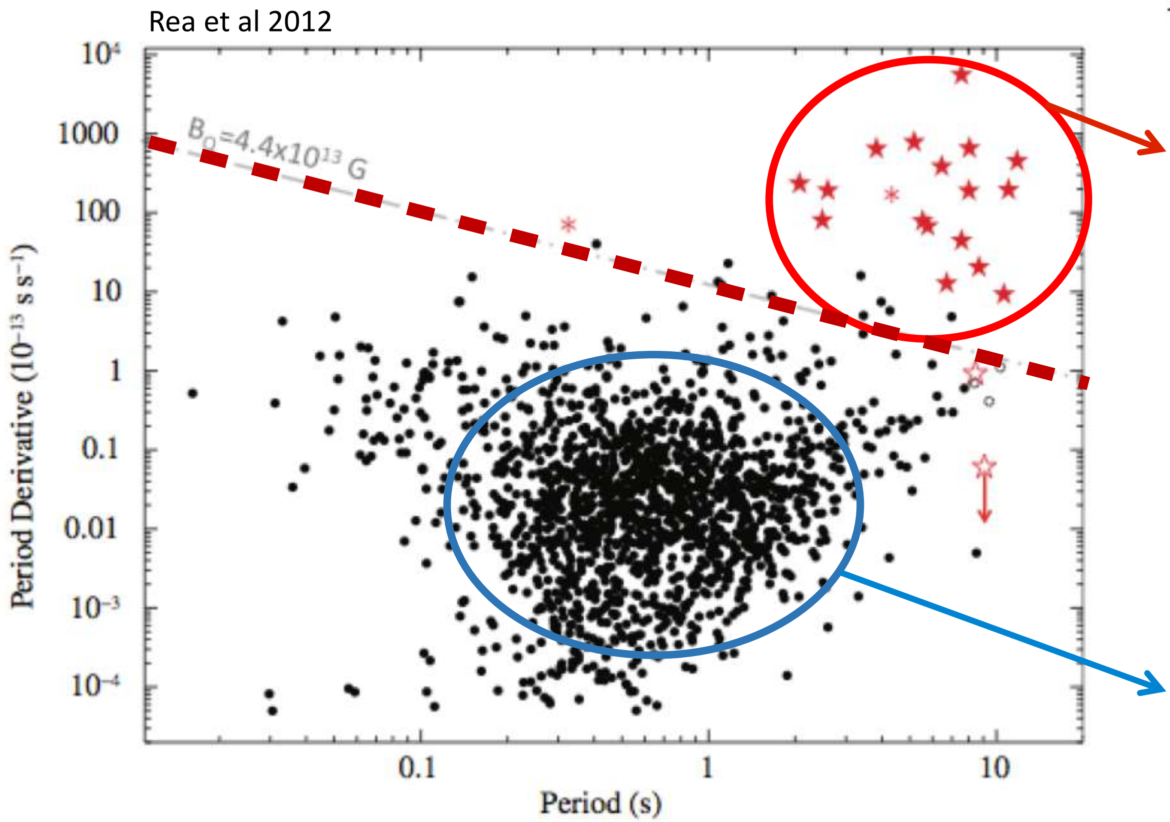
Collaborateurs :

Alexis Reboul-Salze
Paul Barrère
Matteo Bugli

Magnetars: the most intense known magnetic fields



$$B_{\rm dip} \propto \sqrt{P\dot{P}} \sim 10^{14} - 10^{15}\,{\rm G}$$

Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

$B \sim 10^{14} - 10^{15}$ G

Pulsars

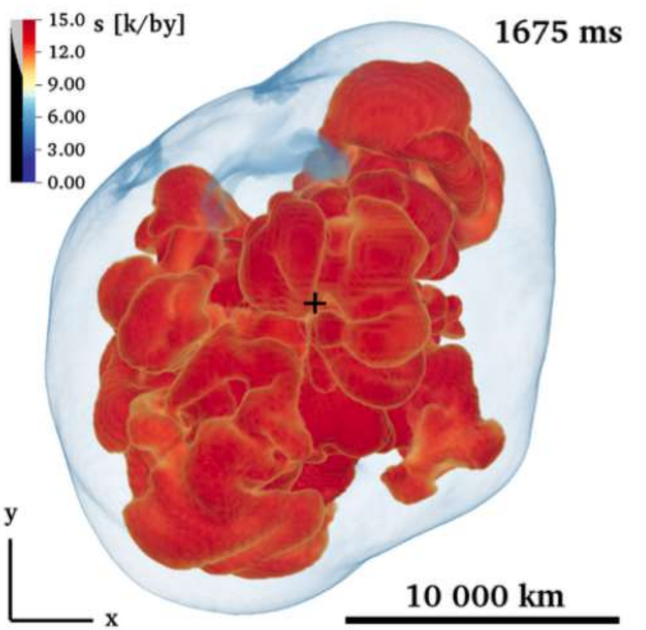
$B \sim 10^{12} - 10^{13}$ G

Outstanding stellar explosions: millisecond magnetars ?

Explosion kinetic energy :

Typical supernova: 10^{51} erg

→ Neutrino driven explosions ?

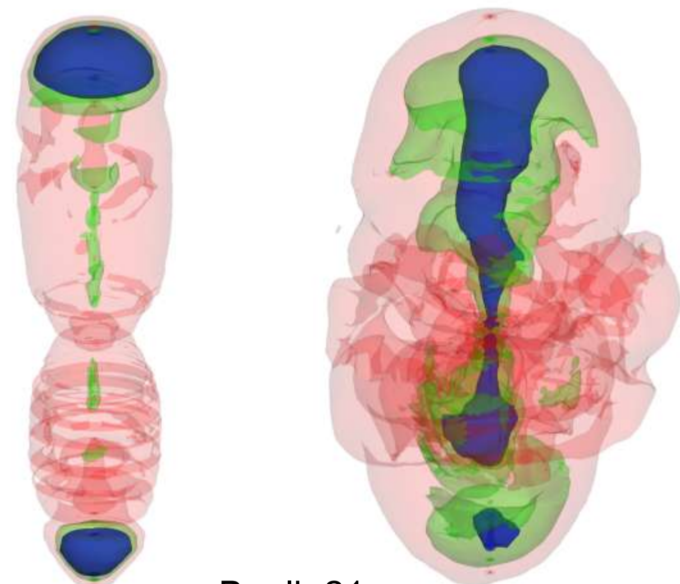


Bollig+20

Rare hypernova & long GRB: 10^{52} erg

aka type Ic BL

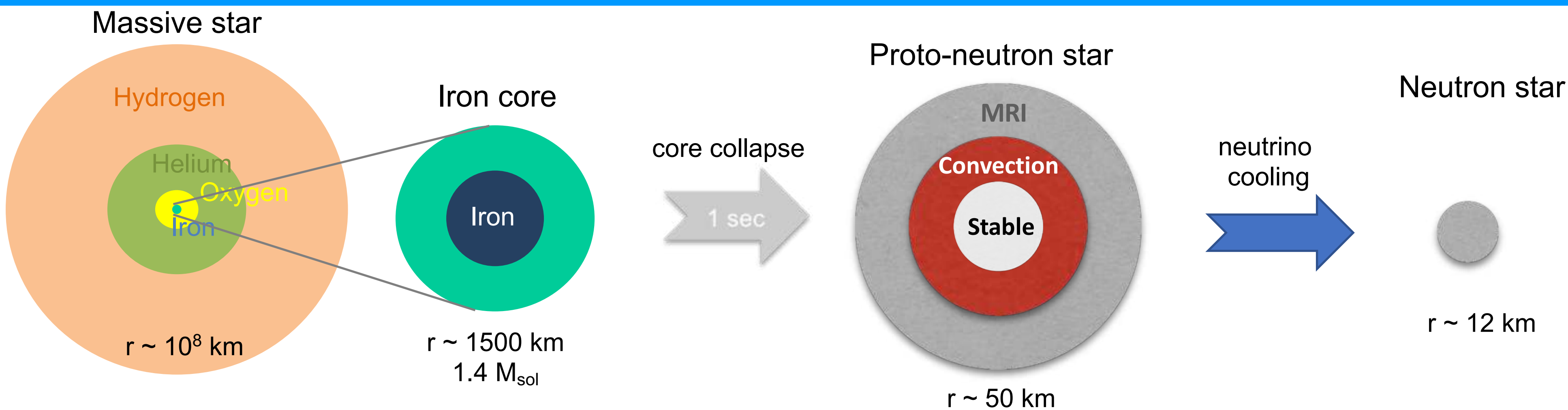
→ Magnetorotational explosion ?



Bugli+21

e.g. Burrows+07, Takiwaki+09,11, Moesta+14, Obergaulinger+17,20, Kuroda+20

Different scenarios for magnetar formation



Compression of stellar magnetic field :

Amplification by a few ~10^4 during core collapse

Very magnetised stars on surface (B >1 kG) : also need a 10^{10}-10^{11} G in the iron core

Protoneutron star dynamos

Magnetorotational instability

Similar to accretion disks

Convective dynamo

Similar to planetary & stellar dynamos

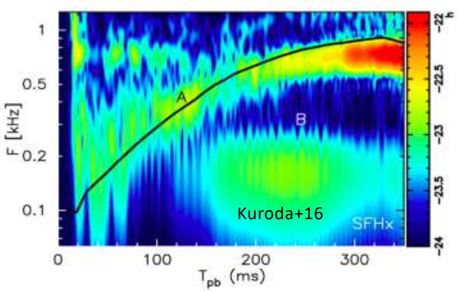
Tayler-Spruit dynamo

Similar to stellar radiative zones

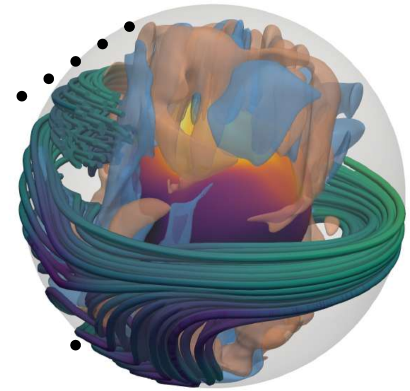
A complementary approach: CCSN models and PNS models

CCSN simulations

- Magnetorotational explosions & long GRBs
- Nucleosynthesis
- Multi-messenger observables



Bugli+21



3D-MHD PNS models

Study magnetar formation

- Fine characterisation of dynamo processes and large scale field generation
- Extensive parameter studies
- Derivation of physics informed scaling laws

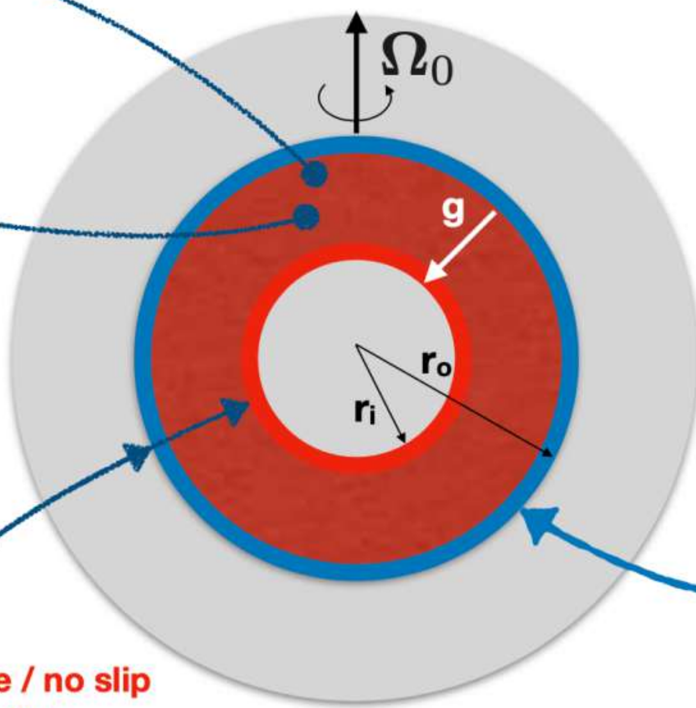
3D modelling of protoneutron star dynamo

Taken from 1D CCSN

Input:
- Temperature profile
- Density profile

Transport coefficients:
- Kinematic viscosity ν
- Thermal diffusivity κ
- Magnetic diffusivity η

github.com/magic-sph/magic



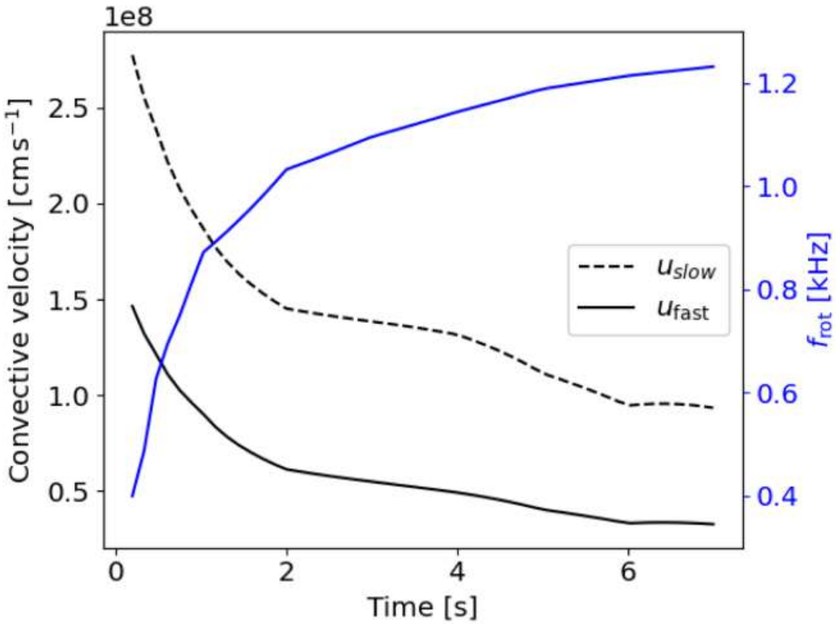
Boundary conditions:
- **Mechanical:** stress-free / no slip
- **Thermal:** fixed entropy flux
- **Magnetic:** perfect conductor ($B_{//}$) / pseudo-vacuum ($B_\perp$)

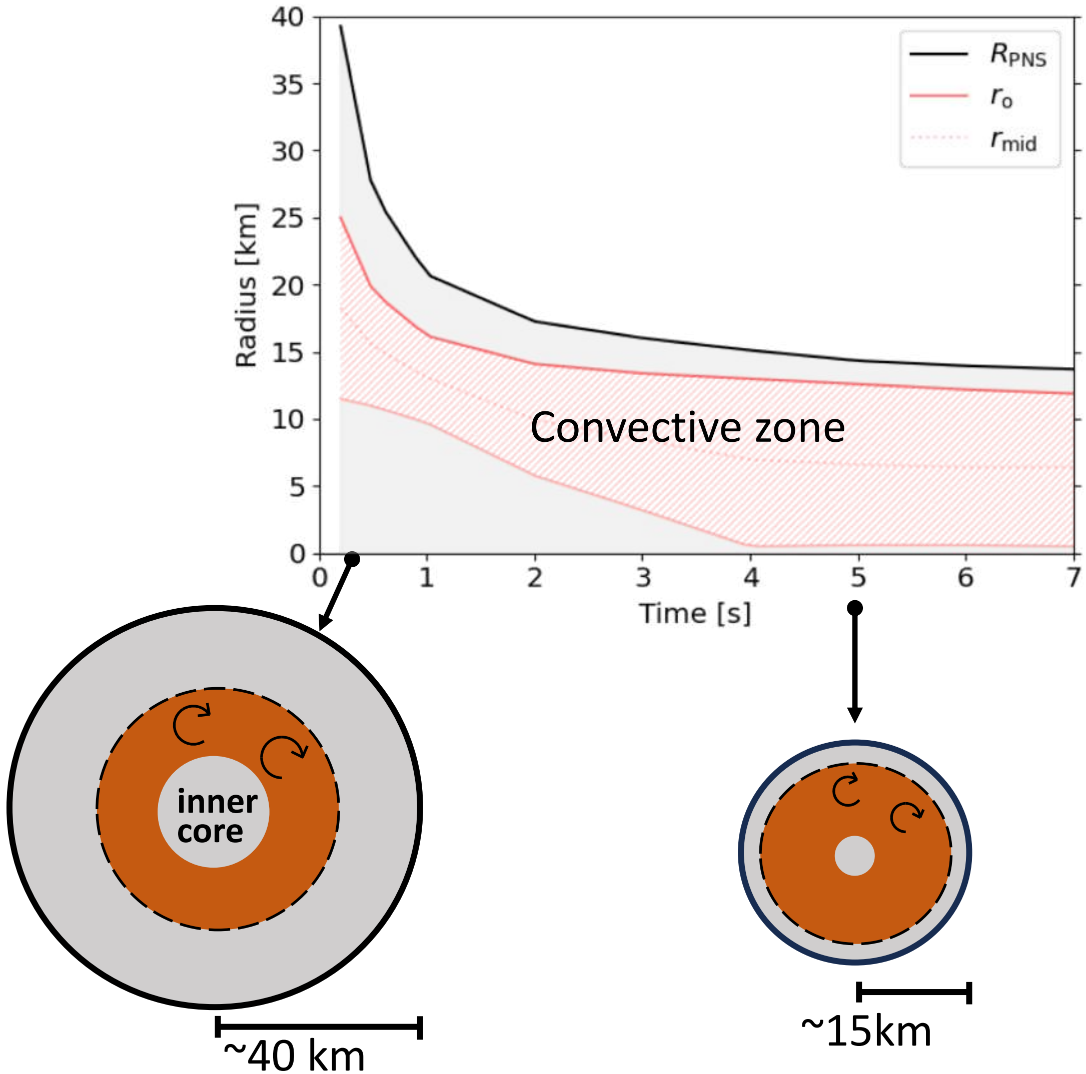
Hypothesis:
- Spherical geometry
- Adiabatic stratification
- Low Mach convection
- 2nd order diffusion approximation for the neutrino transport
- Electrical conductivity of degenerate, relativistic electrons

- Orders of magnitude

$$\begin{cases} \Phi_o \sim 10^{52}\,\mathrm{erg/s} \\ r_o \sim 25\,\mathrm{km} \\ T_o \sim 10^{11}\,\mathrm{K} \\ \varrho_o \sim 10^{13}\,\mathrm{g/cm^3} \\ \nu_o \sim 10^{10}\,\mathrm{cm^2/s} \\ \kappa_o \sim 10^{12}\,\mathrm{cm^2/s} \\ \eta_o \sim 10^{-3}\,\mathrm{cm^2/s} \end{cases}$$

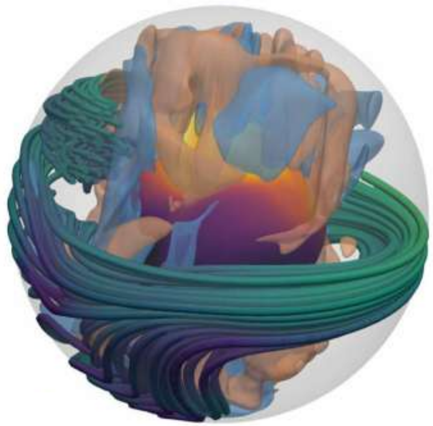
Protoneutron star time evolution

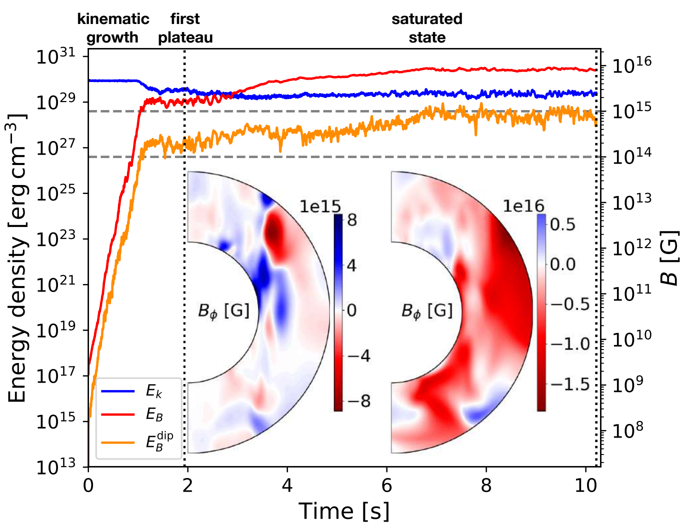




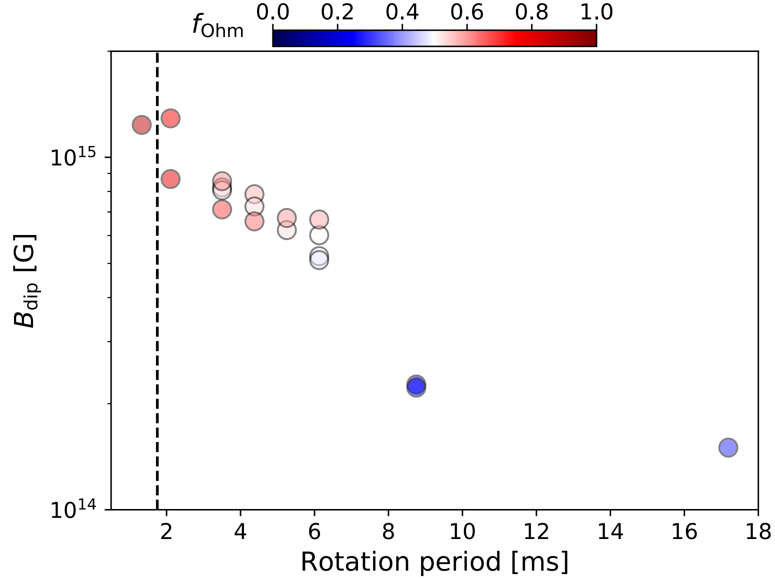
Two branches of convective dynamo

Fast rotation : strong branch

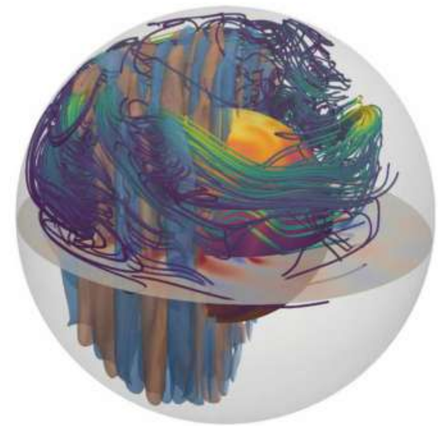




Dipolar magnetic field



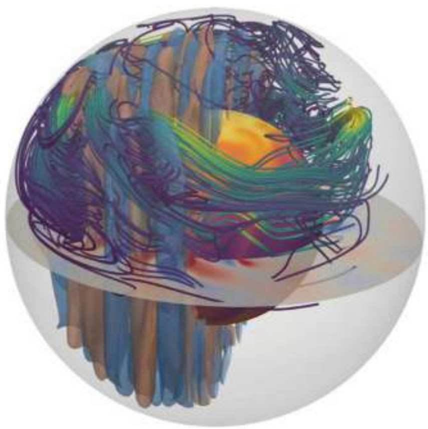
Slow rotation : weak branch



Raynaud et al 2020

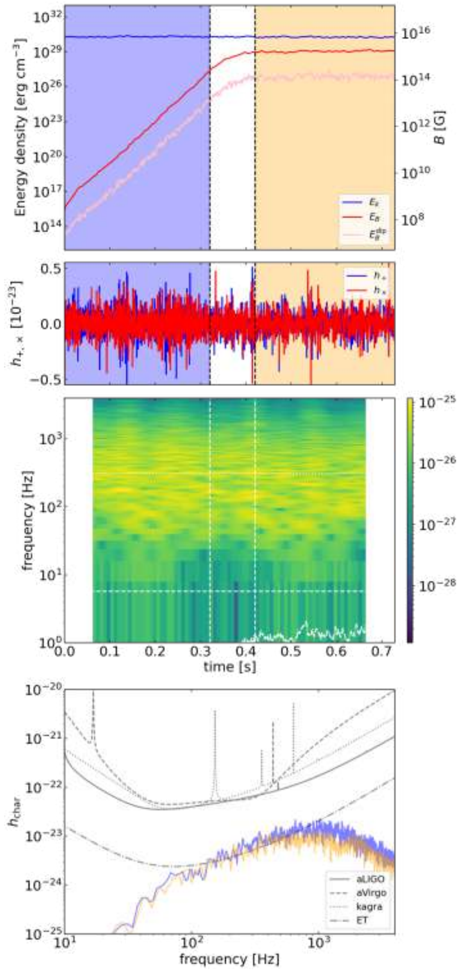
GW from PNS convective dynamo

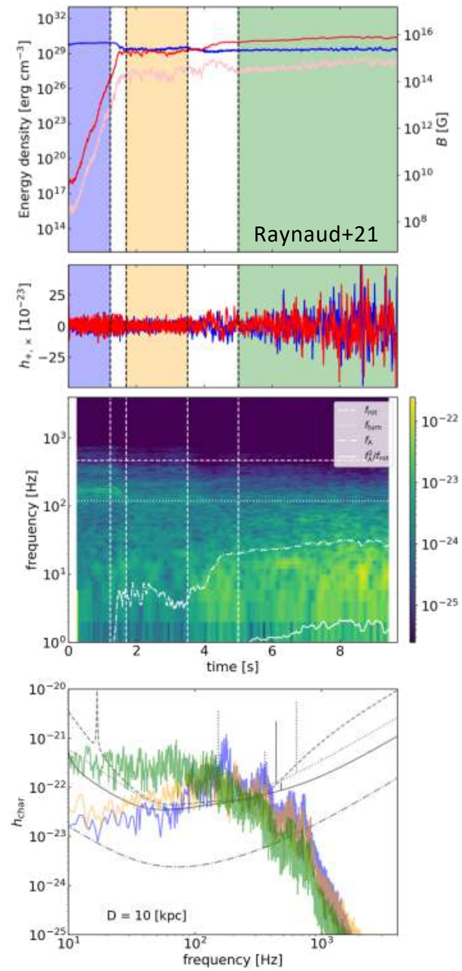
$P = 175\text{ms}$



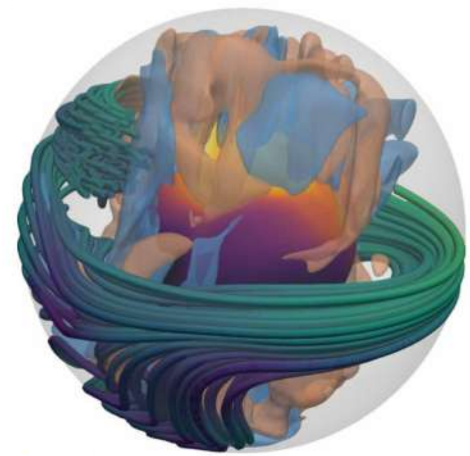
Weak branch

$$\frac{E_B}{E_{\text{kin}}} \lesssim 1$$





$P = 2.1\text{ms}$



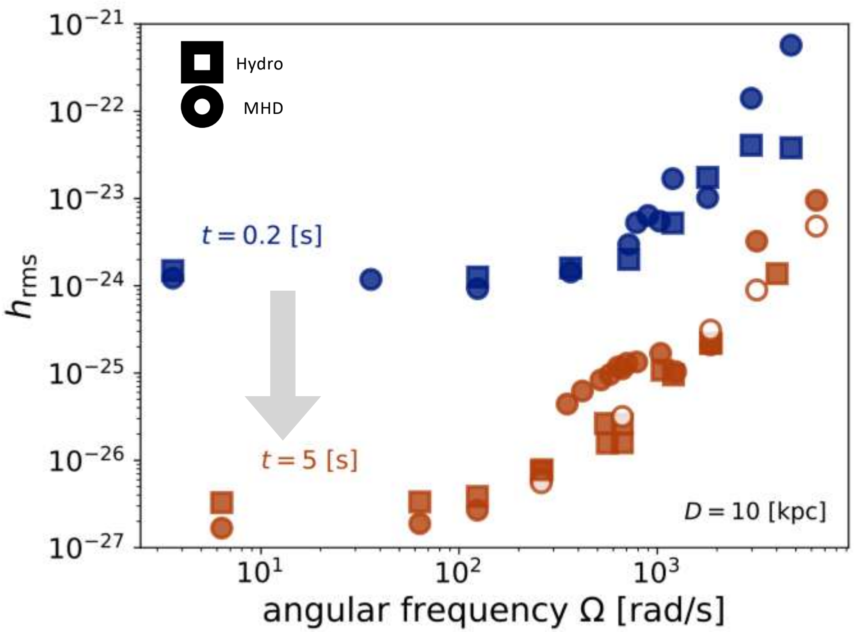
Strong field dynamo

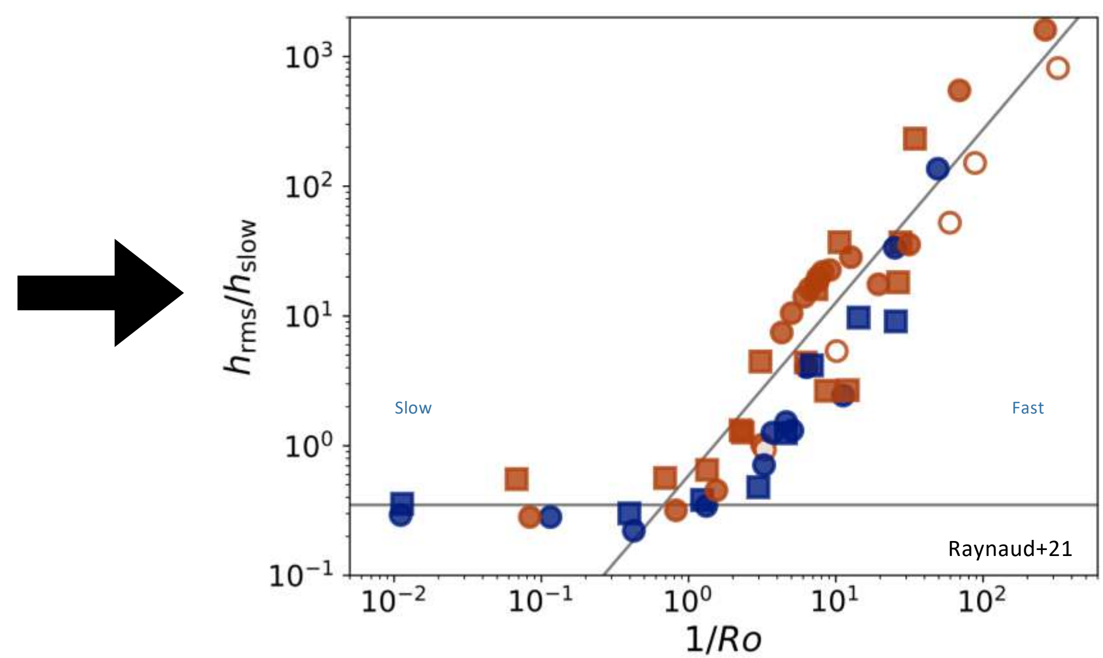
$$\frac{E_B}{E_{\text{kin}}} \propto \left(\frac{U}{\Omega d}\right)^{-1} \equiv Ro^{-1} \gg 1$$

$$B_{\text{dip}} \sim 10^{15}\text{G}$$
$$B_{\text{tor}} \sim 10^{16}\text{G}$$

Raynaud+20

GW amplitudes



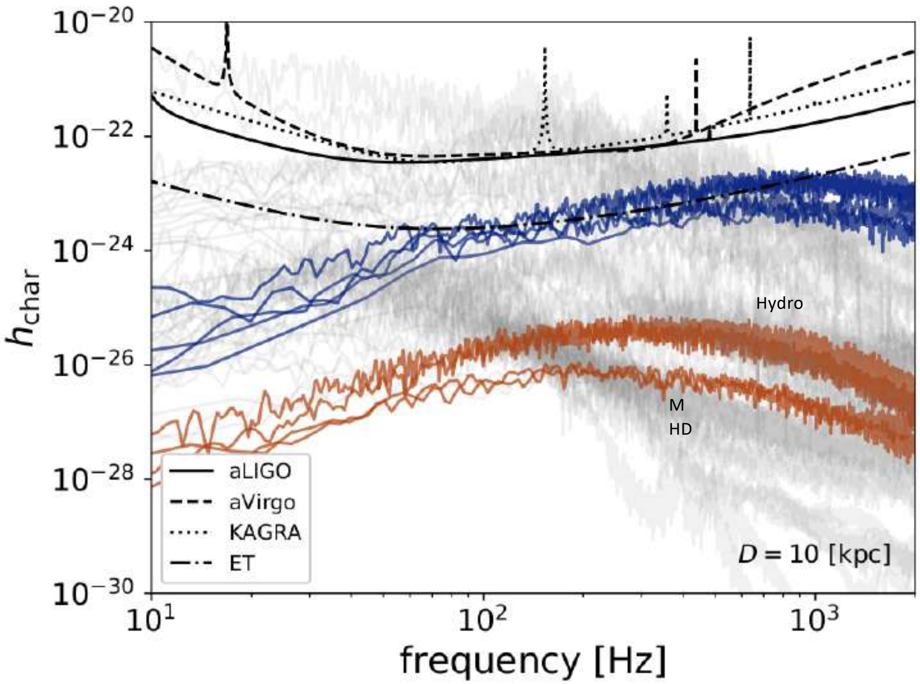


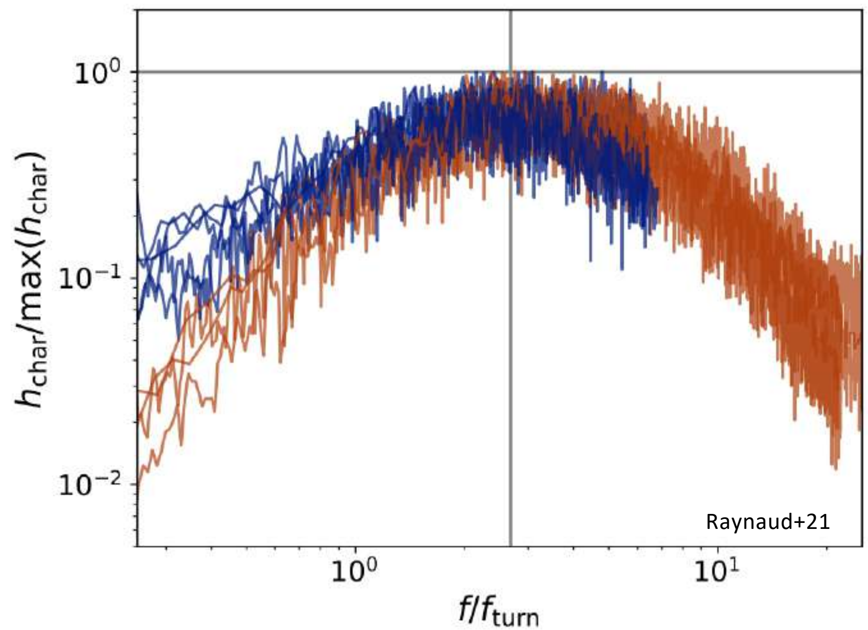
State-of-the-art rotating convection scalings (Aurnou+20)

- Slow rotation: $f_{turn} \gg f_{rot} \Leftrightarrow Ro \gg 1$
- Fast rotation: $f_{turn} \ll f_{rot} \Leftrightarrow Ro \ll 1$

with the Rossby number $Ro \equiv \frac{U}{\Omega d}$

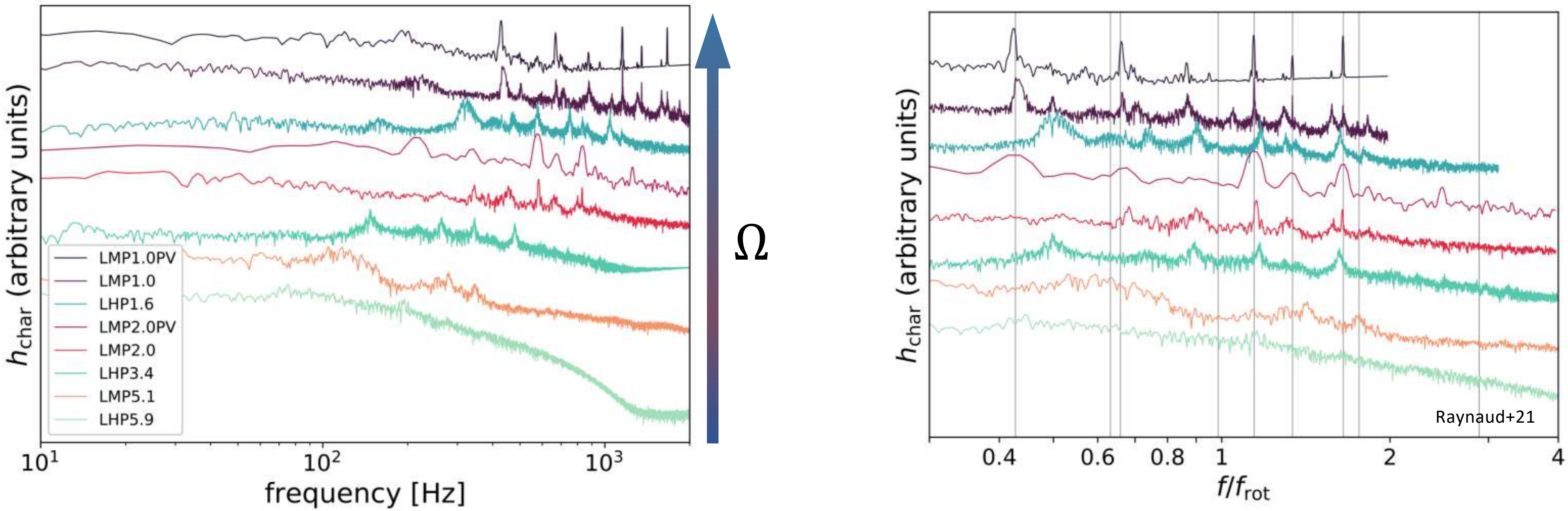
Frequency scaling: slow rotating regime





$$f_{\max} \propto f_{\mathrm{turn}} \equiv u_{\mathrm{rms}}/d$$

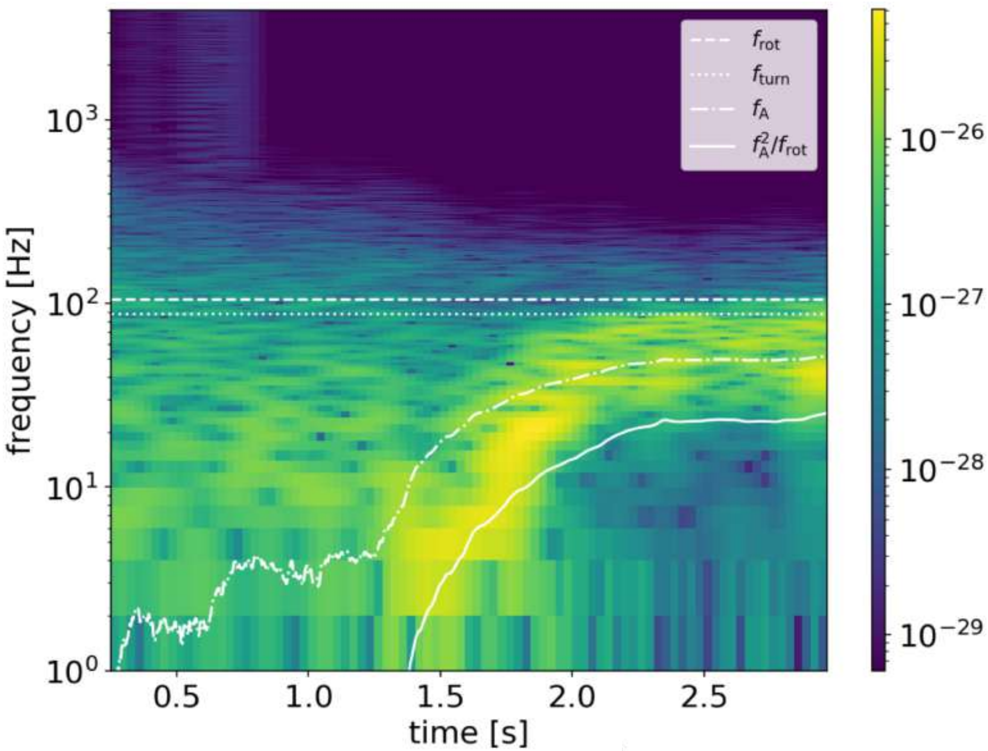
Frequency scaling: fast rotating regime

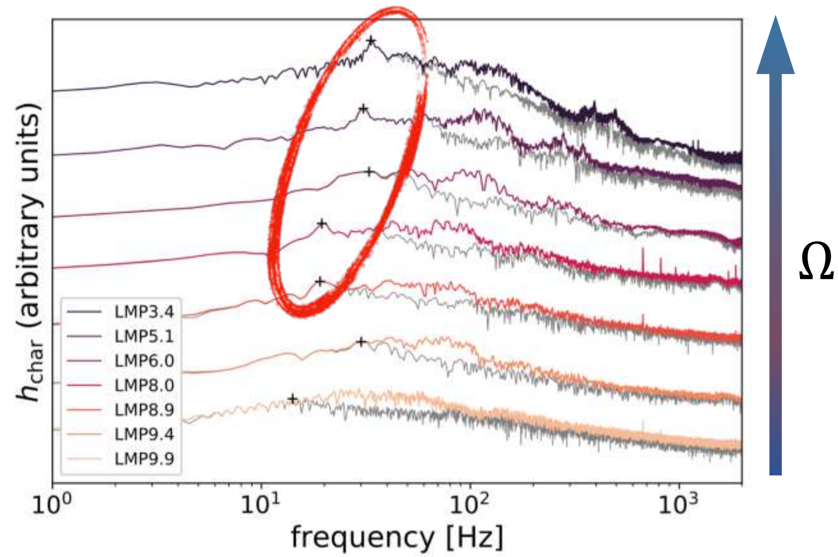


Inertial modes

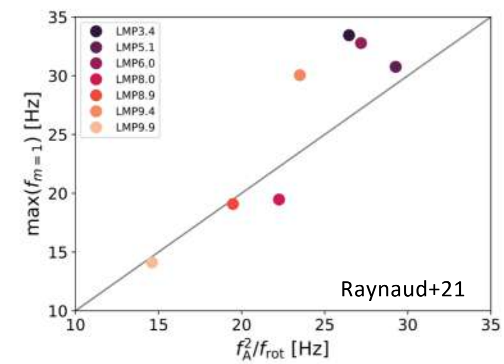
$$f_{\text{peaks}} \propto f_{\text{rot}}$$

Strong field dynamo growth





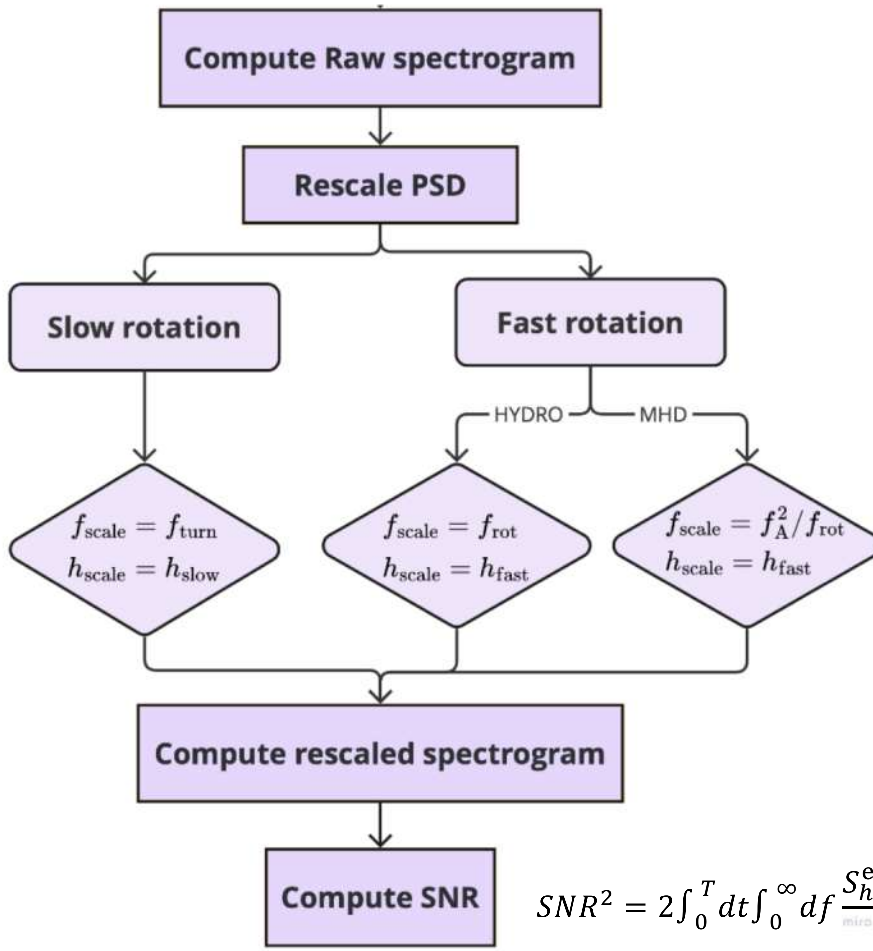
Rossby $m = 1$ mode modified by magnetic effects $f \propto f_A^2 / f_{\rm rot}$



Rescaling procedure to predict detectability

Hypotheses

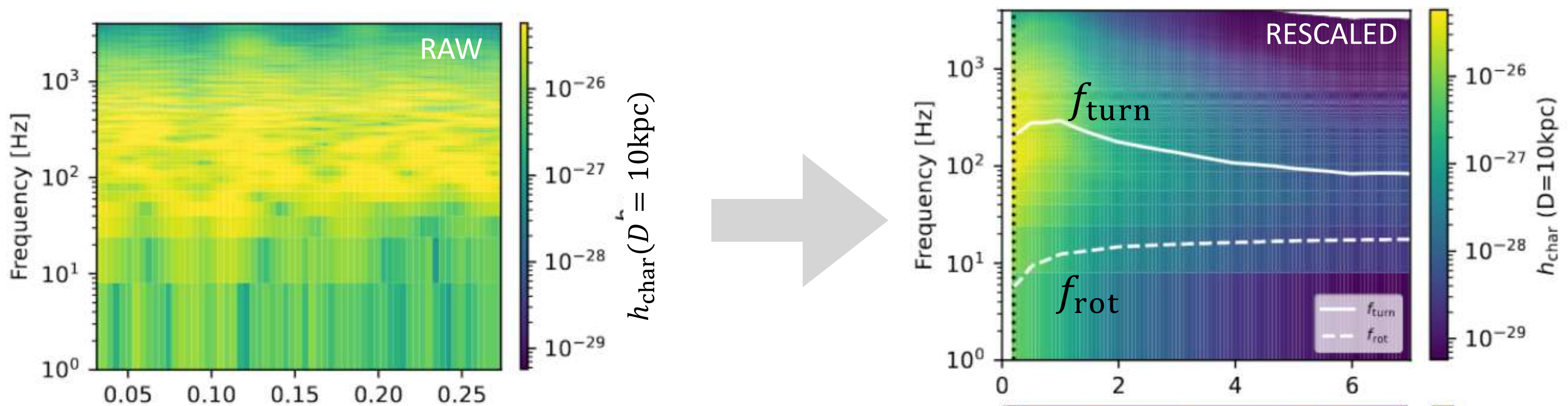
- From the 3D models
  - Self-similarity of the PSD
  - Frequency & amplitude scaling relations
- From the 1D model
  - PNS evolution from 0.2 s to 7 s
- Angular momentum conservation $\Longrightarrow \Omega(t)$
- Asymptotic regimes : $Ro > 1 or Ro < 1$



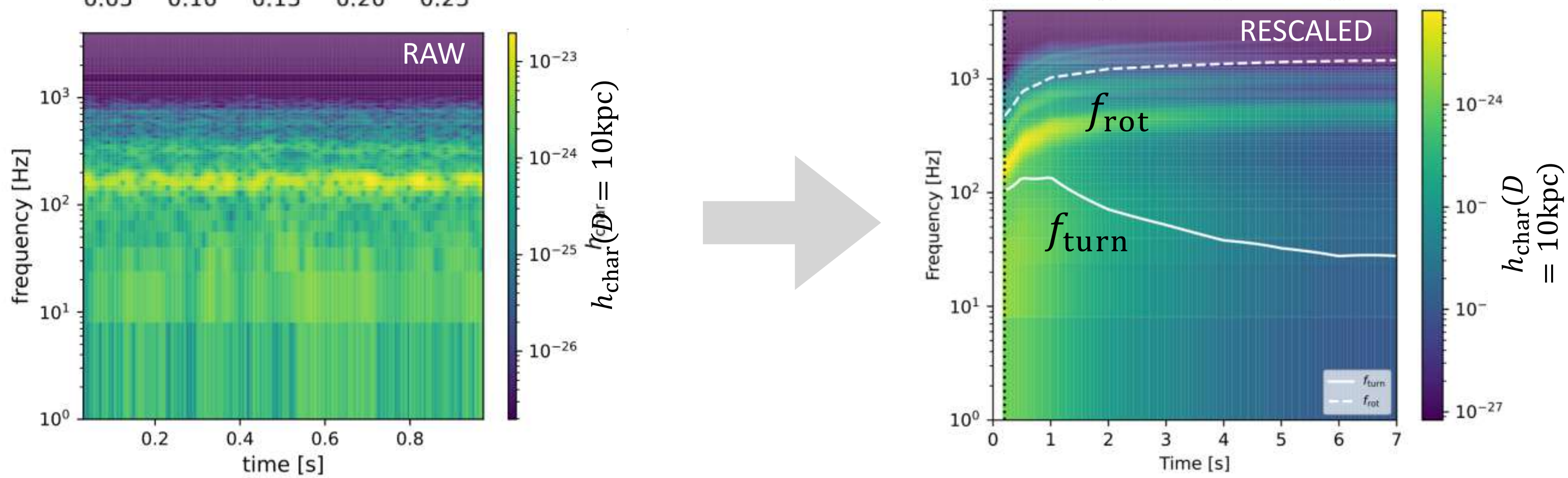
$$SNR^2 = 2\int_0^T dt \int_0^\infty df \, \frac{S_h^{\rm evol}(f,t)}{S_n(f)} = \int_0^T \sigma(t)d$$

Rescaled spectrograms

Slow rotation

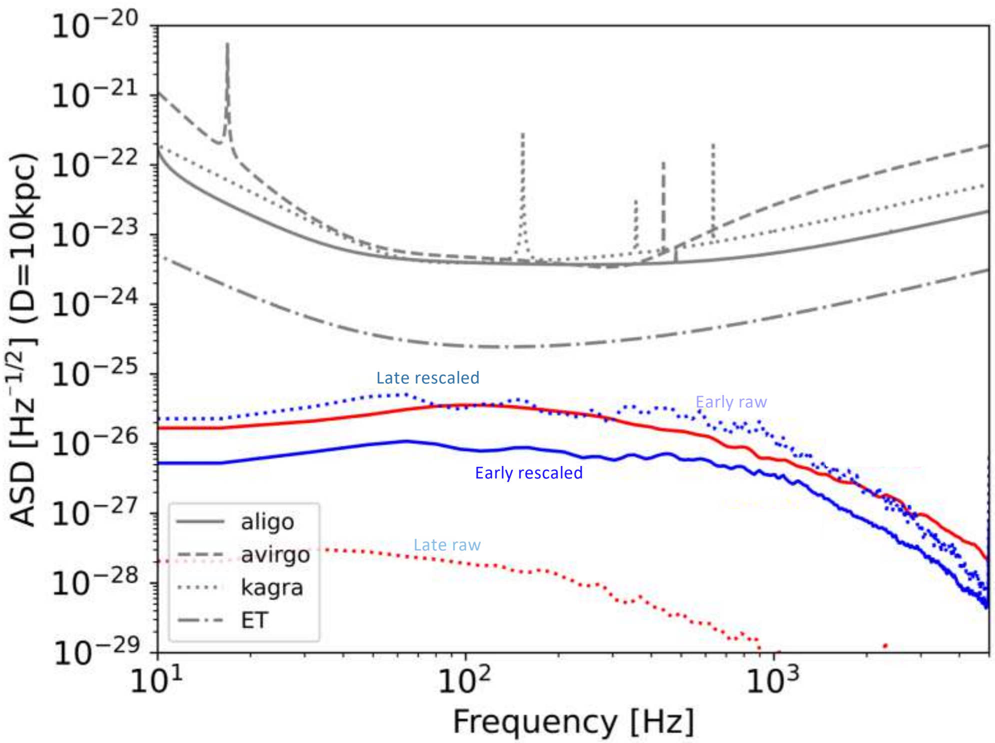


Fast rotation

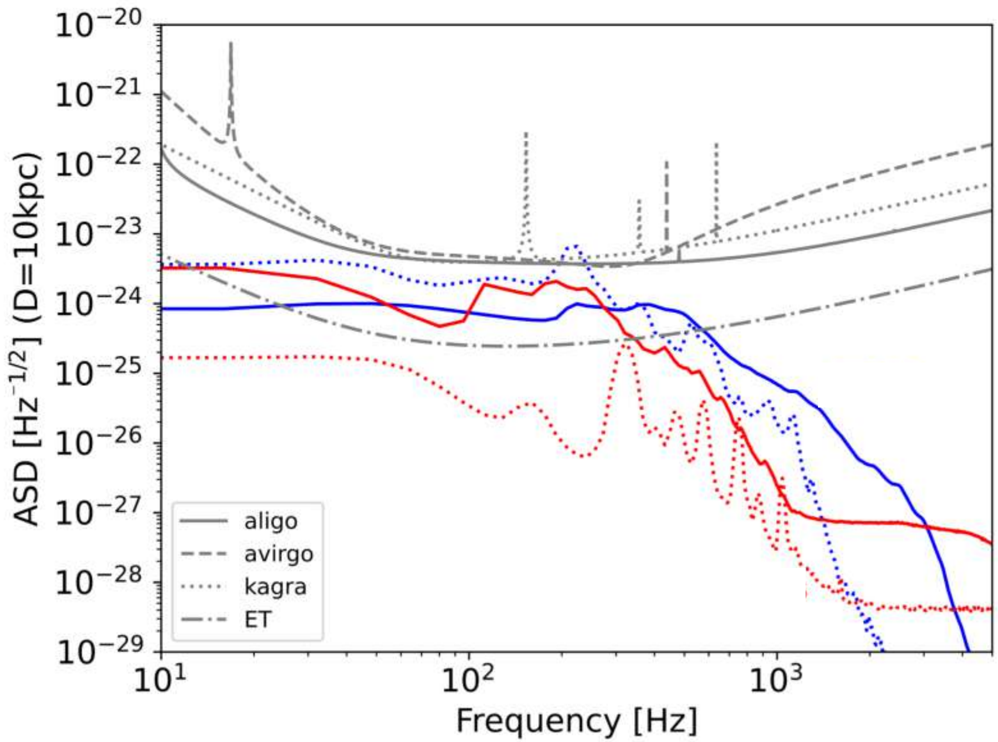


Rescaled spectra

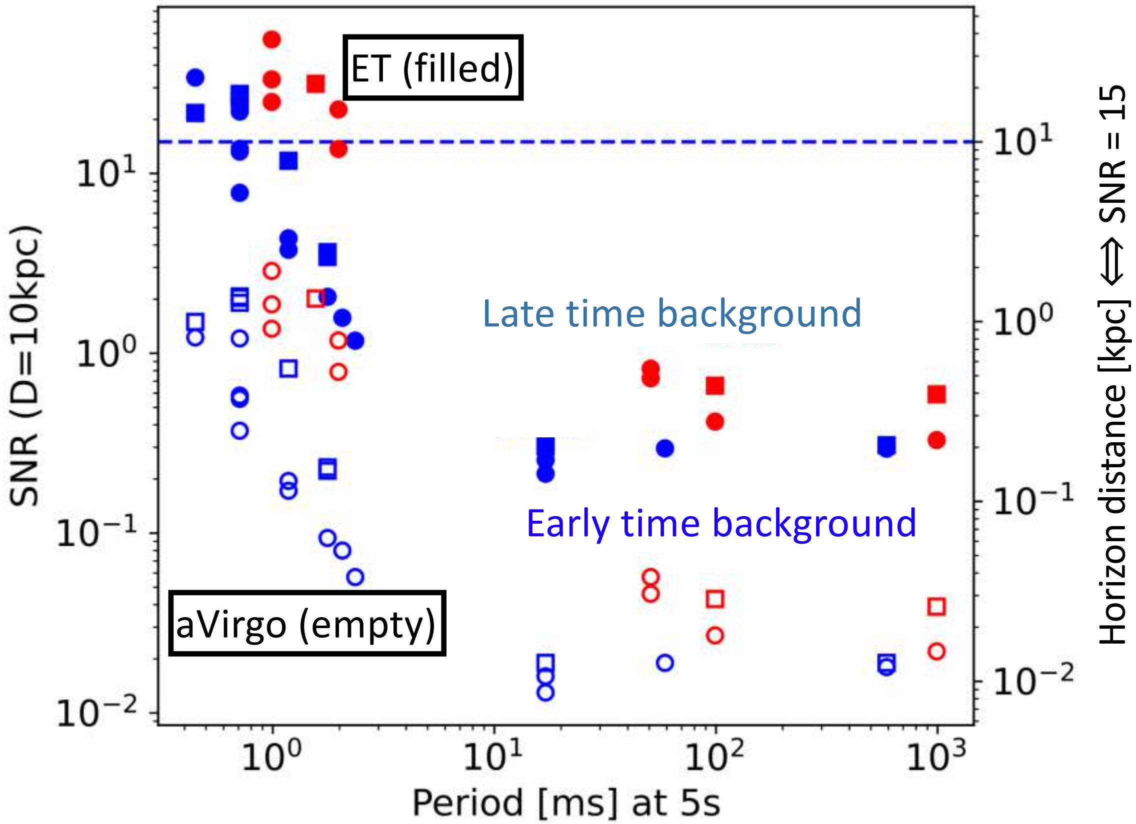
Slow rotation



Fast rotation



Signal to noise ratio with current and 3rd gen. detectors



Conclusion

Characteristics of GW from PNS convection:

Slow rotation

- Broad spectrum
- $f_{\max} \propto f_{\mathrm{turn}}$
- Weak impact of magnetic field
- SNR ~ O(0.1) @ 10 kpc with ET

Fast rotation (= Magnetar formation ?)

- h_{rms} strongly increases with rotation
- Complex spectra with inertial modes
- Possibly low frequency, strong field dynamo signature
- SNR ~ O(10) @ 10 kpc with ET

Perspectives

- Coupling with a stable zone to study the excitation of g-modes by turbulent convection
- Characterization of the different PNS dynamo scenarios

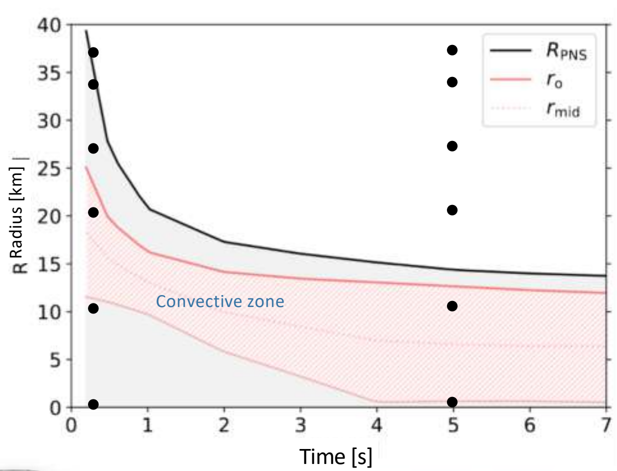
Refs:
Raynaud+20,22

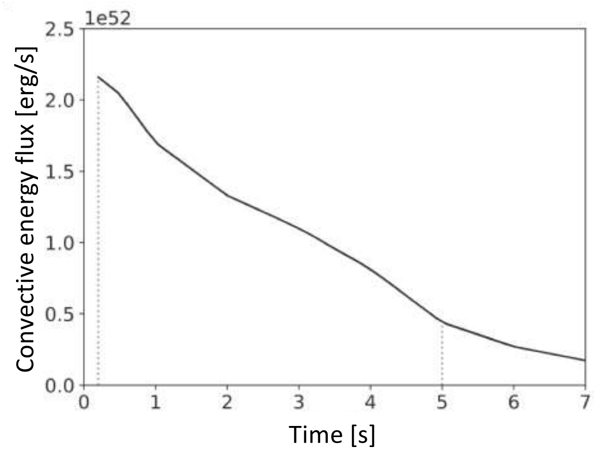
Other dynamo scenarios:
Barrère+22,23,24
Reboul-Salze+21,22, Guilet+22

Thank you !

Thank you !

PNS convection: 1D preview





Source

Lorenz Hüdepohl's PhD thesis

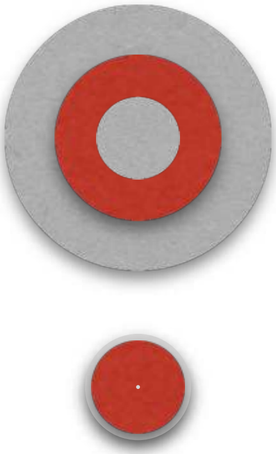
Prometheus-Vertex code

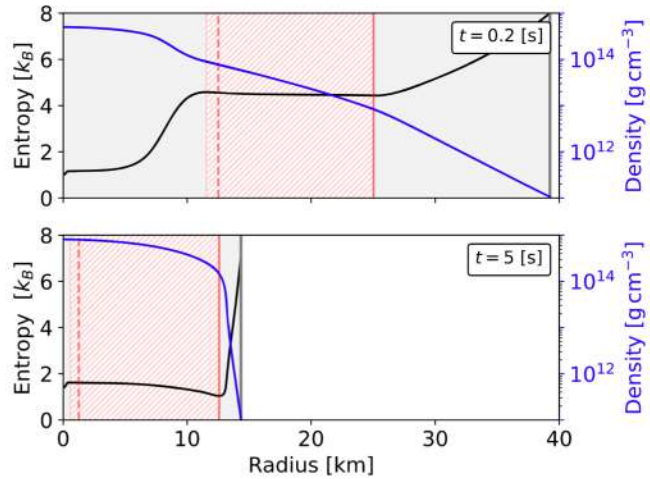
1D model + MLT

LS220 EoS

27 $M_\odot$ progenitor

PNS baryonic mass 1.78 $M_\odot$





Adiabatic background

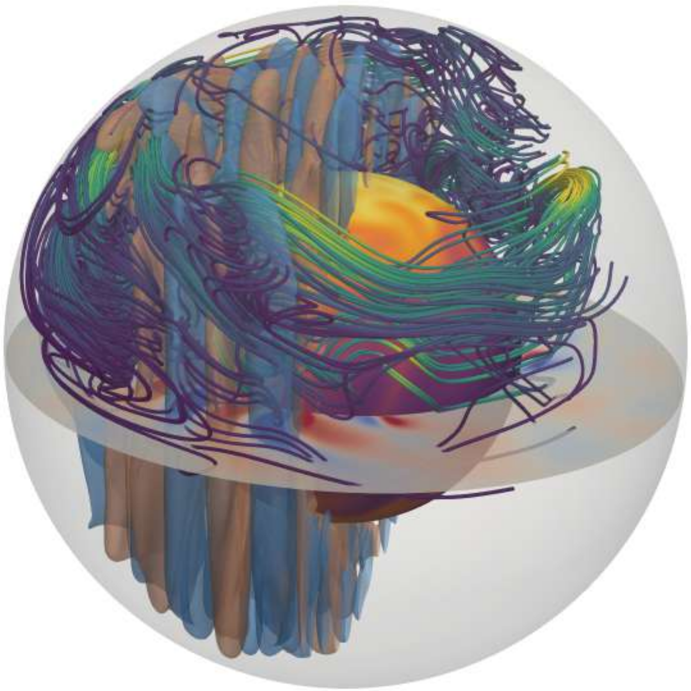
t = 0.2 s ⟺ Early time

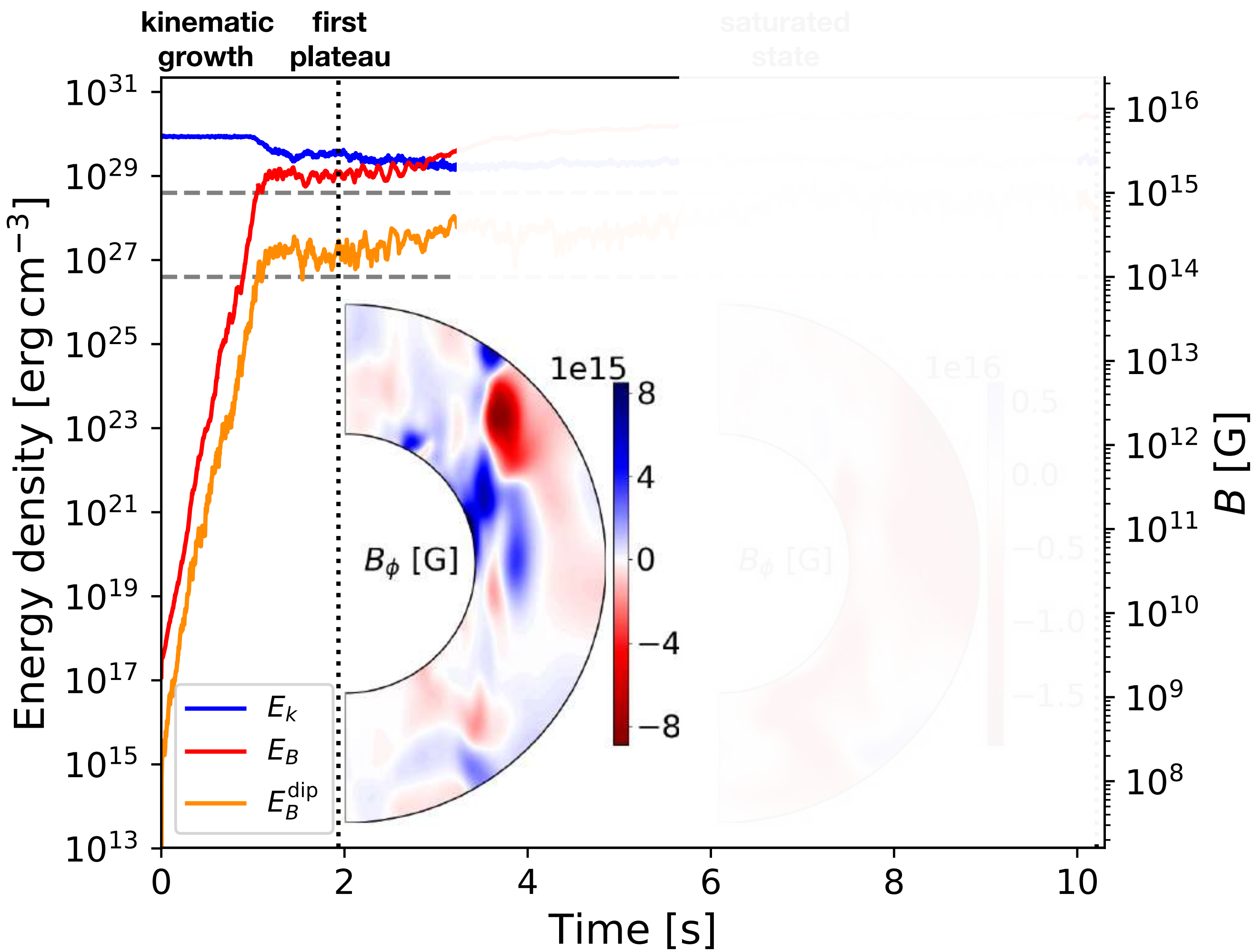
t = 5 s ⟺ Late time

Method

1. stability determined according to the Schwarzschild criterion
2. deduce the shell geometry
3. fit the background profile $(\tilde{\varrho}, \tilde{T})$

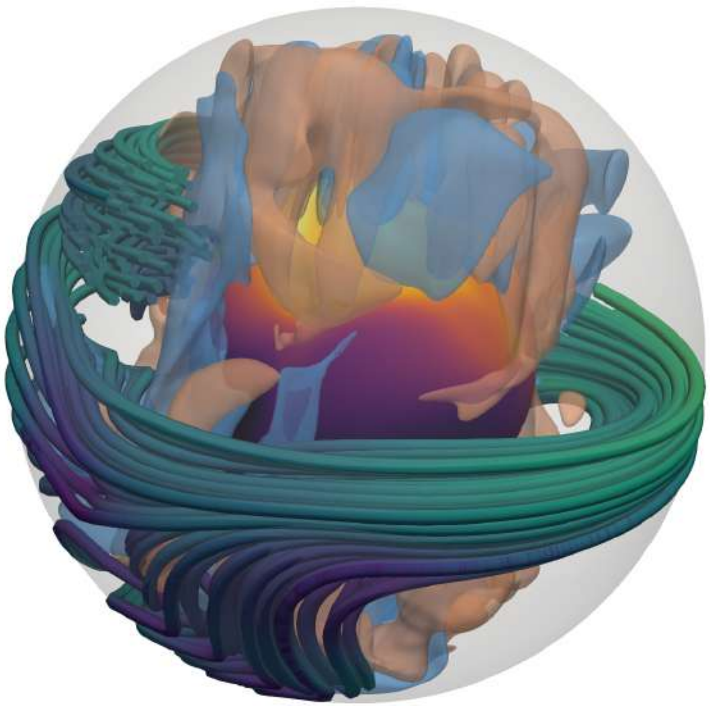
Convective dynamo in a protoneutron star

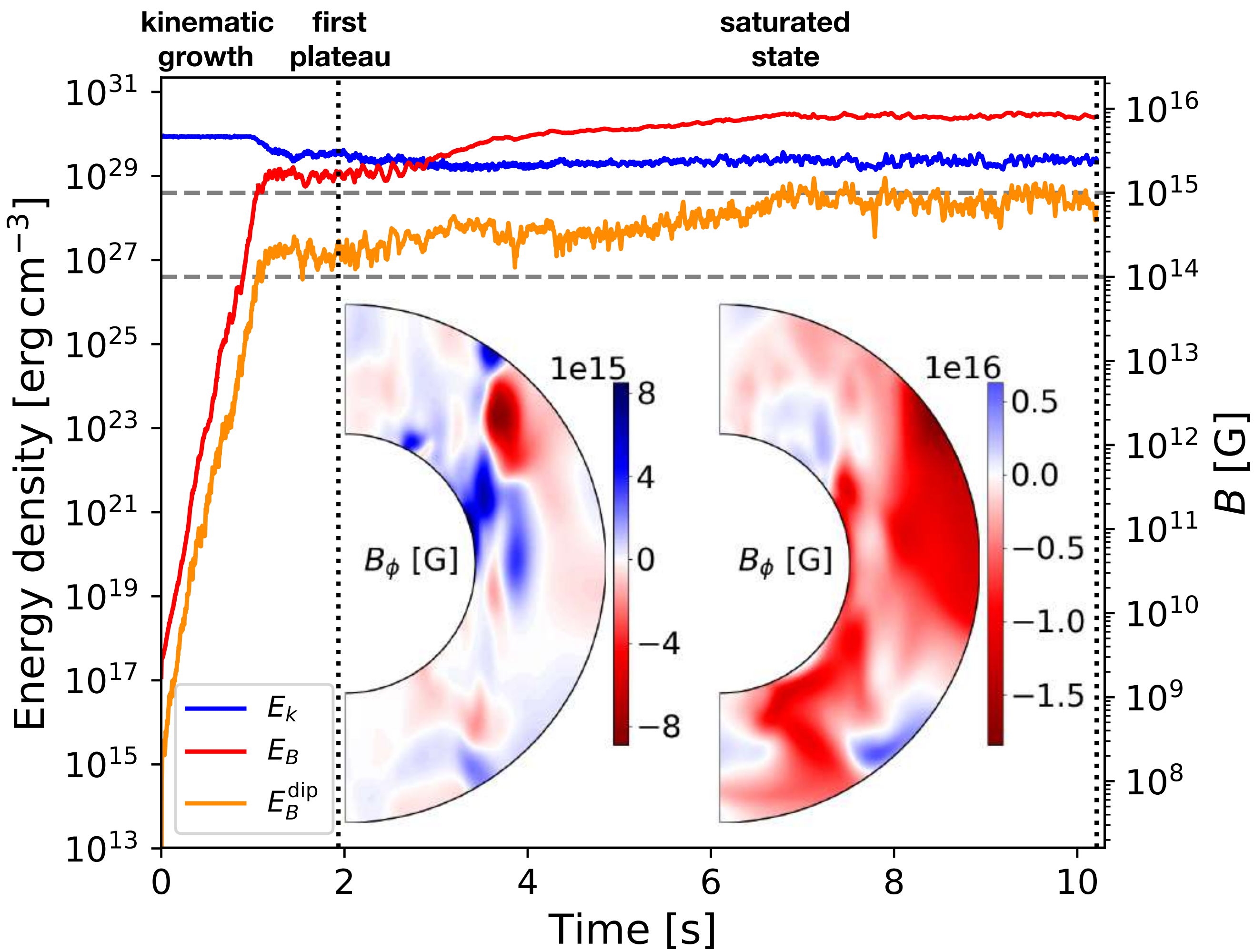




Raynaud et al 2020

Convective dynamo in a protoneutron star





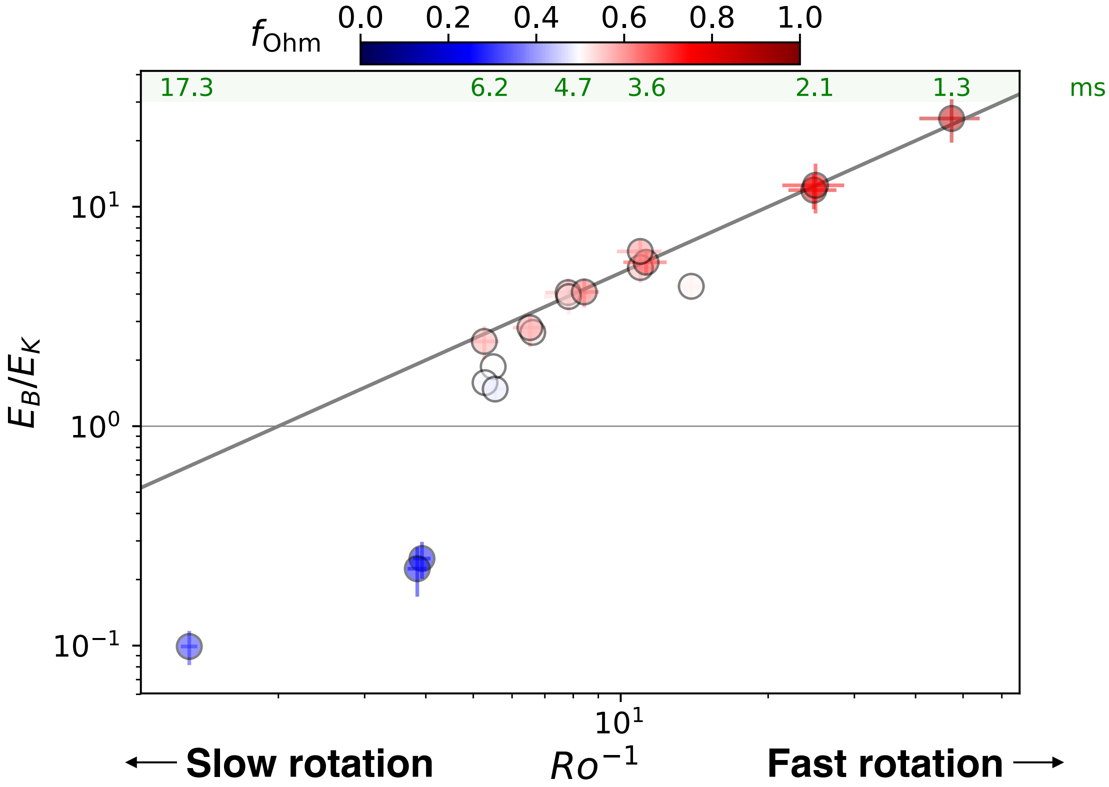
Raynaud et al 2020

Scaling: strong field regime

Magnetostropheric force balance:
Lorentz ~ Coriolis

$$B^2 \propto \Omega \mu \varrho U d \implies \frac{E_B}{E_{kin}} \propto Ro^{-1}$$

Rossby number: $Ro = U/(\Omega d)$



Raynaud+20, see also Roberts78,88 ; Dormy 16 ; Augustson+16 Seshasayanan+19